The Economics of Power Generation Via the Shell Gasification Process

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INTRODUCTION

An SGP-based power station (SGP/PS) is based on the partial oxidation of fuel and differs from a conventional power station (CPS) in the following main aspects:

1. In a CPS the fuel oil is burned with air at atmospheric pressure in a boiler where the heat of combustion is used to produce superheated high-pressure steam.
   In an SGP/PS the fuel oil is first partially oxidized with air at elevated pressure, whereby the fuel oil is converted into a raw fuel gas. This gas, after removal of contaminants such as ash and sulphur, is subsequently burned in a combustor and expanded in a gas turbine.

2. In a CPS all electricity is produced by the expansion of steam in turbo-generators.
   In an SGP/PS electricity is partly produced by expansion of gas in gas turbo-generators and partly by expansion of steam in steam turbo-generators.

The SGP/PS scheme shows the following interesting aspects:

a) Recovery of up to 95% of the sulphur in fuel oil as elemental sulphur is possible with conventional, well proven gas treating and sulphur recovery processes.

b) The high efficiency of electricity generation via the gas and steam turbine cycle compensates for the efficiency loss caused by the processing steps converting the high-sulphur, high-ash residual fuel oil into a clean fuel gas.

c) No emission of particulate matter.

d) Low emission of nitrogen oxides because of low flame temperature.

e) Lower demand for cooling water than in a CPS, since only part of the electricity is raised via the steam expansion (and subsequent steam condensation) cycle.

f) The operation at elevated pressure results in the use of compact, shop-fabricated, equipment.

The schemes discussed here are all based on the use of residual fuel oil as fuel to the power station. The SGP has been developed with special emphasis on the use of heavy residual fuel oil as feedstock and commercial operation of the SGP units has shown that the reliability and on-stream efficiency of the process is high, even in cases where high-ash fuels are being processed. An on-stream efficiency of 95% can be taken as a realistic figure.

At present close to 100 units with a total throughput exceeding 11,000 tons/d fuel have been, or are being, constructed. A power station based on the above concept but using coal as feedstock has been built in Germany.[1]

DISCUSSION

The conversion of the chemical energy of a fuel oil into electricity is usually effected by the following steps (Fig. 1):

a) Complete combustion of the fuel oil with air at atmospheric pressure.

b) Recovery of the heat of combustion by the production of superheated, high-pressure steam.

c) Expansion of the steam through a steam turbo-generator for the production of electricity.

d) Condensation of the steam and recycle of the condensate in the form of boiler feed water to step b).

In this process the sulphur present in the fuel oil is converted into SO_2 and emitted with the flue gas to the atmosphere unless special equipment is installed for the removal of this SO_2[2].

An SGP-based power station[3)-7)] as envisaged here consists of the following steps (Fig. II):

a) Partial oxidation of the fuel oil with air at elevated pressure (10-20 atm.) for the production of raw fuel gas.

b) Removal of the sulphur components (mainly H_2S) from the raw fuel gas.

c) Complete combustion of the clean fuel gas.

d) Expansion of the combusted gas through a gas expansion turbine, coupled with an electric generator, for the production of electricity.

e) Cooling of the gas turbine exhaust gas.

f) Recovery of heat in steps a), c) and e) in the form of high-pressure superheated steam.

g) Expansion of the steam through a turbo-generator for the production of electricity.

h) Condensation of the steam and recycle of the condensate in the form of boiler feed water to steps a), c) and e).

Compared with a conventional oil-fired power station the SGP/PS shows three significant new elements. These are:

1. <u>The fuel gas preparation step</u>

In this step the fuel oil is first partially oxidized in a reactor at elevated pressure (15-25 atm.) with air, whereby the oil is converted into a gas with carbon monoxide and hydrogen as the main constituents.
The sulphur of the fuel oil is mainly converted into hydrogen sulphide, which component can subsequently be removed with a conventional gas-treating solvent.
In Fig. III a scheme is given of the Shell Gasification Process (SGP). The main items of the SGP are:

a) Reactor with combustor/gun assembly.
b) Waste-heat boiler enabling the production of high-pressure steam.
c) Gas scrubber to clean the gas of carbon and ash.
d) Carbon work-up and recycle section.

The operating pressure of these units ranges between atmospheric pressure and around 60 atmospheres. The pressure of the steam raised in the various waste-heat boilers ranges between 30 and 100 atmospheres.

In the case of partial oxidation with air, as envisaged for power station applications, the gas leaving the SGP will have the following composition when starting with a residual fuel oil of 4% wt sulphur:

	% vol. (dry)
H_2	14.7
CO	22.0
CO_2	2.5
H_2S	0.5
COS	0.03
CH_4	0.3
N_2 + A	60.0

This gas is free of soot and ash and is subsequently treated for sulphur removal. Since the gas contains CO_2 as well as the sulphur components H_2S and COS, a number of alternative methods for the removal of the sulphur components and the subsequent conversion of these components into elemental sulphur is to be considered, for instance:

a) Complete removal of COS and H_2S

This is possible by using a mixture of a physical solvent and a chemical solvent such as Sulfinol[8], which consists of Sulfolane (tetrahydrothiophene 1.1 dioxide) and DIPA (di-iso propanol amine). Such solvent completely removes the H_2S and the COS but at the same time completely co-absorbs the CO_2. This results in a considerable dilution of the H_2S feed to the subsequent Claus unit, where the H_2S is converted into sulphur. A special design for the Claus unit is therefore required in this case. An overall sulphur recovery of 95% can be obtained.

b) Selective removal of H_2S

This is possible by using a chemical solvent such as di-iso propanol amine (Shell Adip process)[8], which completely removes the H_2S but only part of the CO_2 and COS. In this way a reasonable H_2S concentration in the feed to the Claus unit is obtained, making the design of the Claus unit simpler but at the cost of a lower overall sulphur removal efficiency, which will be of the order of 85-90%. By incorporating special design features in the sulphur recovery unit (Claus unit), this figure can be increased by up to 5 points.

2. <u>The supercharged boiler</u>

The clean fuel gas, as produced in the gasification/ desulphurization section, is burnt in a supercharged boiler at about 10-20 atm. In this boiler the high-pressure saturated steam produced in the waste-heat boilers of the gasification unit is superheated. The supercharged boiler has the following advantages:

a) By application of such a boiler the steam conditions are made independent of the gas turbine outlet temperature. This means that the steam superheat temperature can be 540°C instead of 350 to 400°C if the steam is superheated in a non-fired gas turbine exhaust boiler installed downstream of a gas turbine with an inlet temperature of 850 to 950°C (present-day technology for industrial gas turbines). The higher steam superheat temperature results in a higher net efficiency for the power station. A fired exhaust boiler, although superior to a non-fired one, would show higher stack losses as compared with a supercharged boiler.

b) The high gas pressure and the high heat transfer rates result in a compact boiler, which is fully shop-fabricated.

c) It is expected that the nitrogen oxides emission will be lower than in direct combustion of the gas in the gas turbine combustion chamber.

By controlling both the combustion air dosage and the amount of steam superheated in the boiler, the temperature of the gas leaving the supercharged boiler can be regulated. This gas is sent to the gas expansion turbine.

3. <u>Gas expansion turbine</u>

The incorporation of gas turbines in natural gas (or light distillate fuel) fired power stations is finding increasing application both because of the high efficiencies that can be obtained and/or because the capital cost for such power stations is relatively low[9]. An important aspect of using a gas expansion turbine is that the inlet temperature of such a turbine can be considerably higher (at present 850°C - 950°C) than the temperature at which a steam turbine can operate (550°C), this governed by the fact that steam-raising and superheating at higher temperatures, as well as providing suitable turbine casings for high-pressure/high-temperature steam, meets with great technical problems. The combination of a gas expansion turbine cycle with a steam expansion cycle therefore enables the conversion of heat into electricity, starting at a very high temperature level, which favourably affects the conversion efficiency.

Another important aspect relevant to the use of gas turbines in power stations is the reliability and availability of the gas turbine. The use of gas turbines in power stations generally has been confined to those power stations that are operated for peak-shaving purposes, for which duty the low capital costs are of advantage and availability is of lesser importance. Recent reports indicate that the availability of the gas turbine cycle can be better than that of the steam turbine cycle[9] and also that long periods between maintenance are being obtained[10]. An example of the increasing confidence in the reliability and availability of gas turbines is their use in high-capital natural gas liquefaction plants[11]. As already stated, it seems unlikely that a steam temperature above 550°C can be obtained, mainly because of very great material problems encountered in the design of the steam turbine, boiler and superheater. There are, however, promising indications that, through a combination of blade cooling techniques and blade material developments, the allowable inlet temperature of gas turbines will continuously be increased. This means that the efficiency of converting heat into electricity can be expected to gradually increase for power stations incorporating gas turbines. In Fig. IV a forecast of gas turbine inlet temperature progression, as given by United Aircraft[12], is presented.

EFFICIENCY OF SGP-BASED POWER STATIONS

The combination of the various elements of an SGP/PS, as described above, together with a conventional steam cycle leads to a power station (Fig. V) where the efficiency loss caused by the clean fuel gas preparation step is compensated to a great extent by the high heat-to-electricity conversion efficiency obtained through the incorporation of the gas turbine. In Table I the effect of the gas turbine inlet temperature on the overall efficiency of the SGP/PS is shown.

Table I

Efficiencies of SGP-based Power Stations[a]

Gas turbine inlet temperature, °C	850	1000	1200	1400
Plant efficiency, %	38.5	40.8	43.0	44.7
Percentage power ex gas turbine cycle, %	24	29	35	40
Steam to be condensed, kg/kWh as % of conventional power station %	87	81	74	69

a) The efficiency of a CPS comprising steam turbines with an efficiency equal to those used in the above SGP-based power stations was calculated to be 39.5%.

From this table it can be concluded that at a gas turbine inlet temperature of around 900°C the efficiency of an SGP/PS is equal to that of a conventional oil-fired power station. This means that at 900°C the favourable effect of this high temperature level on the overall plant efficiency has fully compensated for the efficiency losses caused by the fuel gas preparation step.

An interesting aspect is that, since in the SGP/PS electricity is generated both by a gas expansion cycle and by a steam expansion cycle, considerable freedom exists in optimizing towards alternative aspects such as efficiency, capital outlay and cooling water requirement. If, for instance, thermal pollution is an important consideration, the cooling water requirement can be reduced by diverting part of the steam into the gas expansion cycle. In this way electricity generation via the gas expansion cycle is increased, and the cooling water requirement for steam condensation is decreased. This scheme would of course at the same time decrease electricity generation via the steam cycle and would result in consumption of boiler feed water. It has been calculated, for instance, that at 850°C turbine inlet temperature a steam injection into the gas turbine inlet stream at a rate of 2.5 kg/kg power station oil feed would have the following effects (compare Table I):

Percentage power ex gas turbine cycle would increase from 24% to 36%. Steam to be condensed would be reduced from 87% to 60% (kg/kWh as % of conventional power station). Plant efficiency would be reduced from 38.5% to 37.7%.

ECONOMICS OF SGP-BASED POWER STATIONS

In Table II the economics of an SGP/PS are compared with those of a conventional power station. Some uncertainty exists about the capital cost figures used for the various SGP/PS schemes given.

This aspect is under investigation.

The additional costs incurred in the SGP/PS as compared to the costs of a conventional power station are charged in this table as a "sulphur removal cost" against the fuel oil used. In this way the operation of an SGP/PS can be compared with alternative ways of removing sulphur from fuel oil.

Such an alternative process is, for instance, the hydrodesulphurization of residual fuel oil (the so-called "direct hydrodesulphurization process"). This process results in desulphurization costs ranging from \$200 to \$360 per ton sulphur removed, depending on crude origin[13] (for residual oils of certain, high ash content, crude types hydrodesulphurization is not yet feasible).

Table II

Economics of SGP-based Power Stations

Basis: 200 MW unit; 6000 hours annual service period; fuel with 4% wt sulphur; 90% desulphurization.
Operating costs plus a capital charge taken as 20.5% on capital (5% for operating, maintenance and overhead, 0.5% for catalysts and chemicals, 15% for repayment of capital, tax and return on capital).
Sulphur credit: \$20/ton.

Conventional Power Station		SGP-based Power Station			
		I	II	III	IV
Turbine inlet temp., °C		850	1000	1200	1400
Plant efficiency, %	39.5	38.5	40.8	43.0	44.7
Capital US \$ x 10^6 a)	40	48-46.5	48-46	48-45	48-44.5
Cost of sulphur removal b)					
\$/ton S	approx. 250 c)	165-134	130-85	96-26	70- -14
¢/barrel/% S	approx. 40 c)	26-21	20-13	15-4	11- -2

a) The capital figures are taken from a 1970 Shell/Sulzer study[3, 7] comparing a 200 MW CPS with a two-stage expansion SGP/PS and escalated for 1972. For Cases I, II, III and IV two assumptions have been made:

1) Capital remains 48 and

2) capital is reduced proportionally with the increase in the gas turbine contribution to power generation.

b) Calculated on the basis of the difference in price between high-sulphur fuel (for the SGP/PS) and the clean fuel (for the CPS) at a constant electricity price.

c) Hydrodesulphurization of long residue (cost can be as high as $360/ton S or ¢57/barrel/% S[13]).

From Table II it can be concluded that an SGP-based power station using currently available gas turbines with an inlet temperature of 850°C results in "sulphur removal costs" that are of the order of 60 to 70% of the costs of alternative desulphurization techniques.

A further increase in the gas turbine inlet temperature would result in a substantial reduction of the "sulphur removal costs" of the SGP-based power station.

CONCLUSIONS

Compared with a conventional oil-fired power station, the SGP/PS has the following attractive characteristics:

1) Some 90% to 95% of the sulphur in the fuel is not emitted to the atmosphere but is recovered as elemental sulphur. The "sulphur removal costs" compare favourably with the costs of alternative desulphurization techniques.

2) No emission of particulate matter.

3) Low flame temperatures are applied, which can be expected to result in low emission of nitrogen oxides.

4) Reduced cooling water requirements.

5) The operation at elevated pressure results in the use of compact, shop-fabricated equipment, which will have a favourable effect on construction time.

References

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[a] Ref. 3 to 6 and 13 are papers, as indicated, presented at the "Seminar of the Desulphurization of Fuels and Combustion Gases", United Nations Commission for Europe, Geneva, 16th-20th November, 1970.

FIG. I

BLOCK SCHEME - CONVENTIONAL POWER STATION

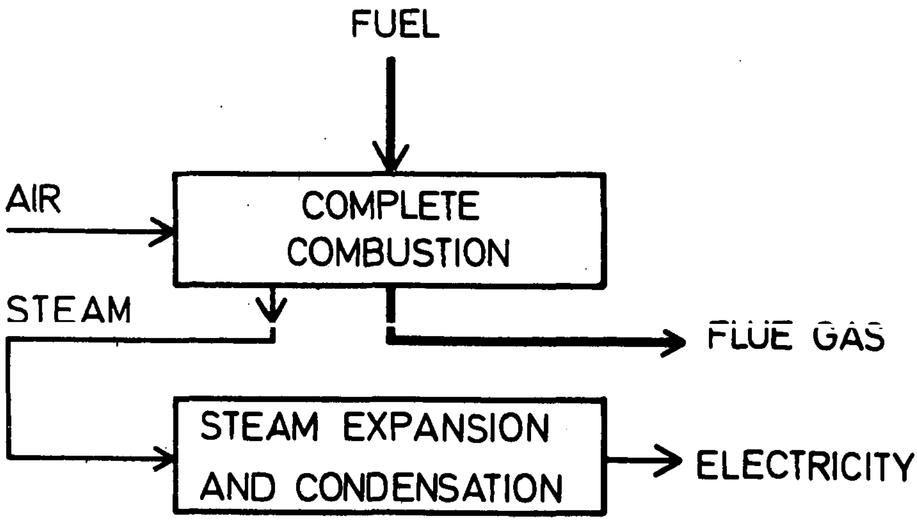

FIG. II

BLOCK SCHEME - PARTIAL OXIDATION BASED POWER STATION

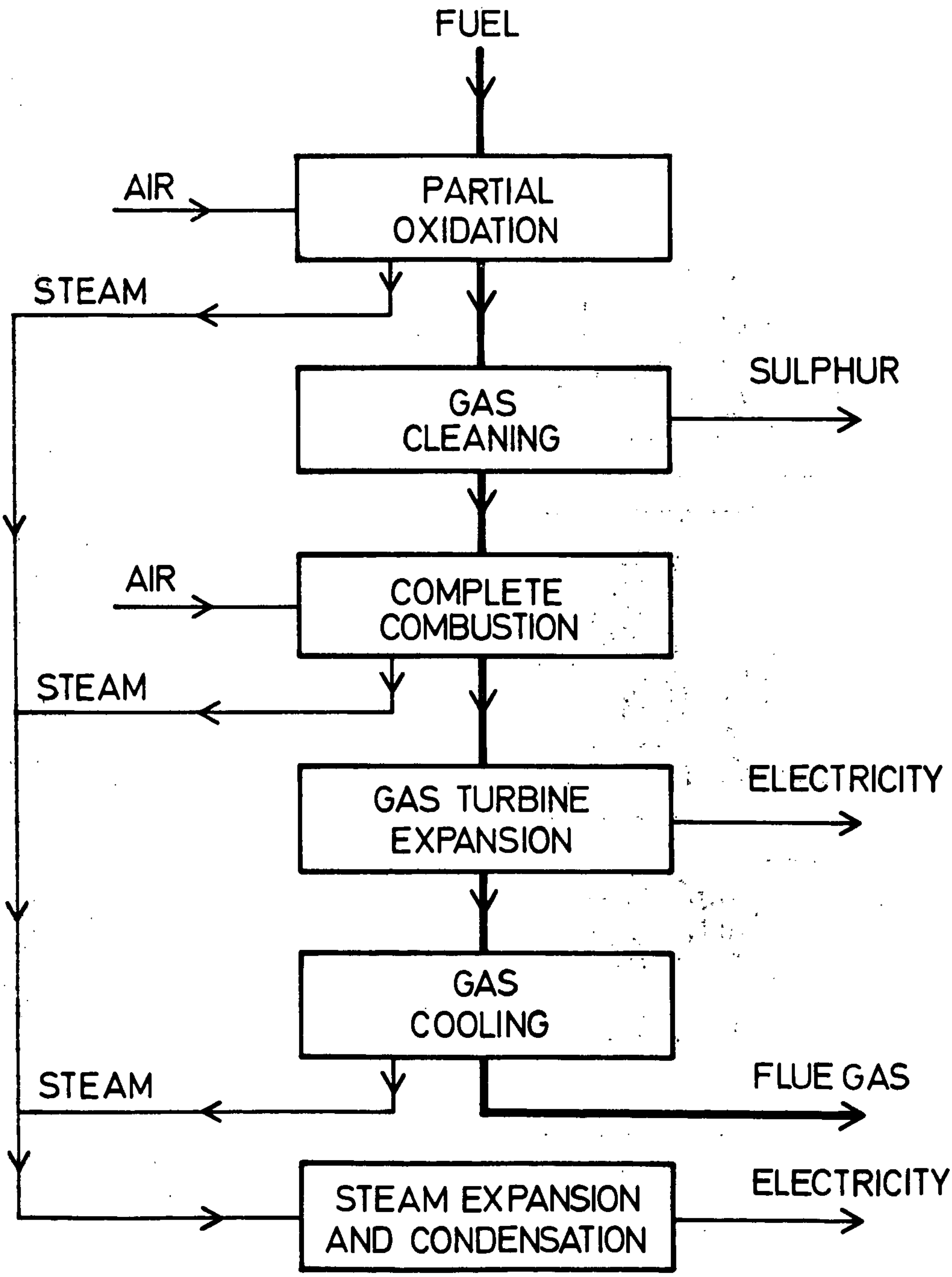

FIG. III
SGP PROCESS WITH CARBON RECYCLE

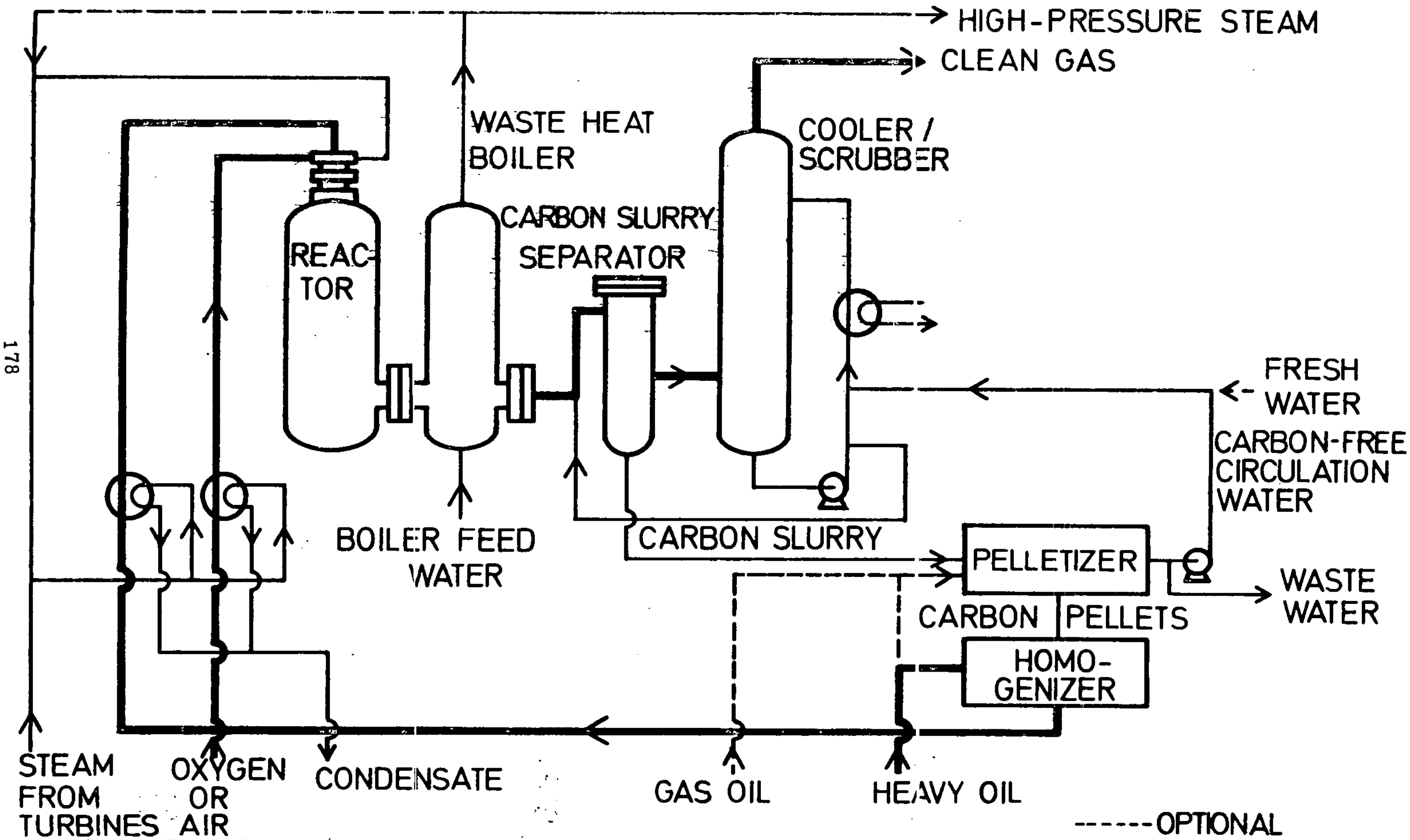

FIG. IV

ESTIMATED TURBINE INLET TEMPERATURE PROGRESSION [8)]

(UNITED AIRCRAFT ESTIMATE)

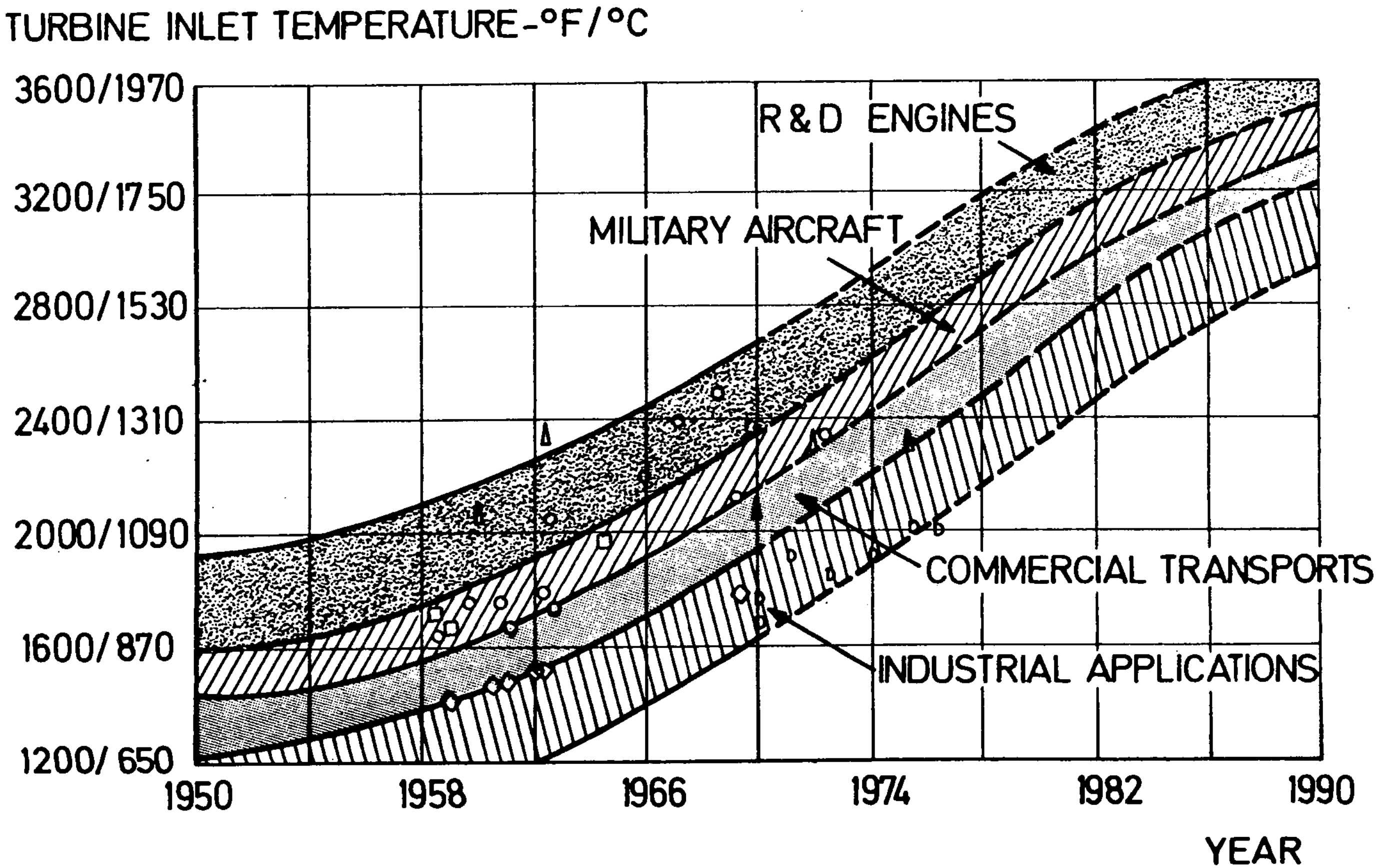

FIG. V
S.G.P.-BASED POWERSTATION